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Temporal Imaging System Demonstrates 103x Magnification and 300 fs Resolution

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Abstract

A temporal imaging system obtaining 103x magnification and 300 fs resolution was demonstrated. This system consists of dispersive delay lines and a time lens produced by sum-frequency generation with a chirped pump.

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The study of transient phenomena with ultrafast detail necessitates the development of new measurement techniques. Temporal imaging[1,2] is an ultrafast pulse manipulation technique that can expand an input waveform while maintaining its original profile thereby allowing data to be recorded with conventional technology. Based on an analogy that exists between paraxial diffraction and narrowband dispersion, the system consists of dispersive delay lines on the input and output combined with a quadratic temporal phase modulation (i.e. a linear frequency chirp) between them acting as a time lens, as shown in Fig. 1. We have demonstrated temporal imaging with 103x magnification and 300 fs resolution.

The f-number of a time lens and thus the system resolution depends inversely on the bandwidth imparted by the modulation process; $f^{\#} = \omega_0/\Delta\omega$. The required bandwidth was obtained from an 87 fs (5.0 THz) pulse from a Kerr-lens modelocked Ti:Sapphire laser which was sent through a grating pair dispersive delay line[3] to obtain the desired linear chirp. When mixed in a 500 μm thick BBO crystal with the dispersed input signal the chirped pump pulse imparts its phase and amplitude profile to the up-converted signal, producing the necessary time lens action[4] for an f-number of 82.

Given the pump pulse chirp rate is $d\omega/d\tau$ we may define a focal group delay dispersion (GDD) as $\phi''_f = -(d\omega/d\tau)^{-1}$ which is the amount of GDD required to remove the phase imparted by the lens. When we cascade an input GDD (ϕ''_1), the time lens, and an output GDD (ϕ''_2), in the proper balance to satisfy the imaging condition, $1/\phi''_1 + 1/\phi''_2 = 1/\phi''_f$, a temporal image with magnification $M = -\phi''_2/\phi''_1$ is created.

Since GDD can be positive or negative it is possible to create temporal images with a single lens having either positive or negative magnification. We designed our system for $M = +100$ using $\phi''_1 = +0.17606$ ps^2 and $\phi''_2 = -17.606$ ps^2, achieved with diffraction grating dispersive delay lines.[3,5] The pump chirp was also obtained with a grating pair and resulted in a focal dispersion of $\phi''_f = +0.17784$ ps^2.

Higher order phase terms produce aberrations in temporal imaging systems. These occur in the spectral phase of the dispersion networks as well as the temporal phase of the time lens. We have discovered that the dominant result of higher order spectral phase in the input of the system is to distort the shape of the system's impulse response whereas when it is in the output it alters the arrival time of the impulse response. Time lens aberrations can produce a variety of effects, including aberrations similar to coma and spherical aberrations in spatial systems. Although our system was configured to minimize the effects of these aberrations, we plan a systematic study of their effects for the future.

A series of temporal images recorded with a 40 GHz photodiode and sampling oscilloscope using a two pulse input sequence are shown in Fig. 2. The delay between the input pulses was changed by 667 fs for each measurement. A change of 68.8 ps was measured in the output image, demonstrating a magnification of $M = +103$. With smaller delays two pulses can still be resolved with approximately 300 fs between them.

In conclusion, we have demonstrated a temporal imaging system with +103x magnification and 300 fs resolution. In addition, since the principles of temporal imaging do not rely on sampling, it should be suitable for extending the range of single-shot waveform recording. It is expected that a scaling of this technology will lead to the realization of a new class of long record length, single transient recorders with ultrafast resolution.

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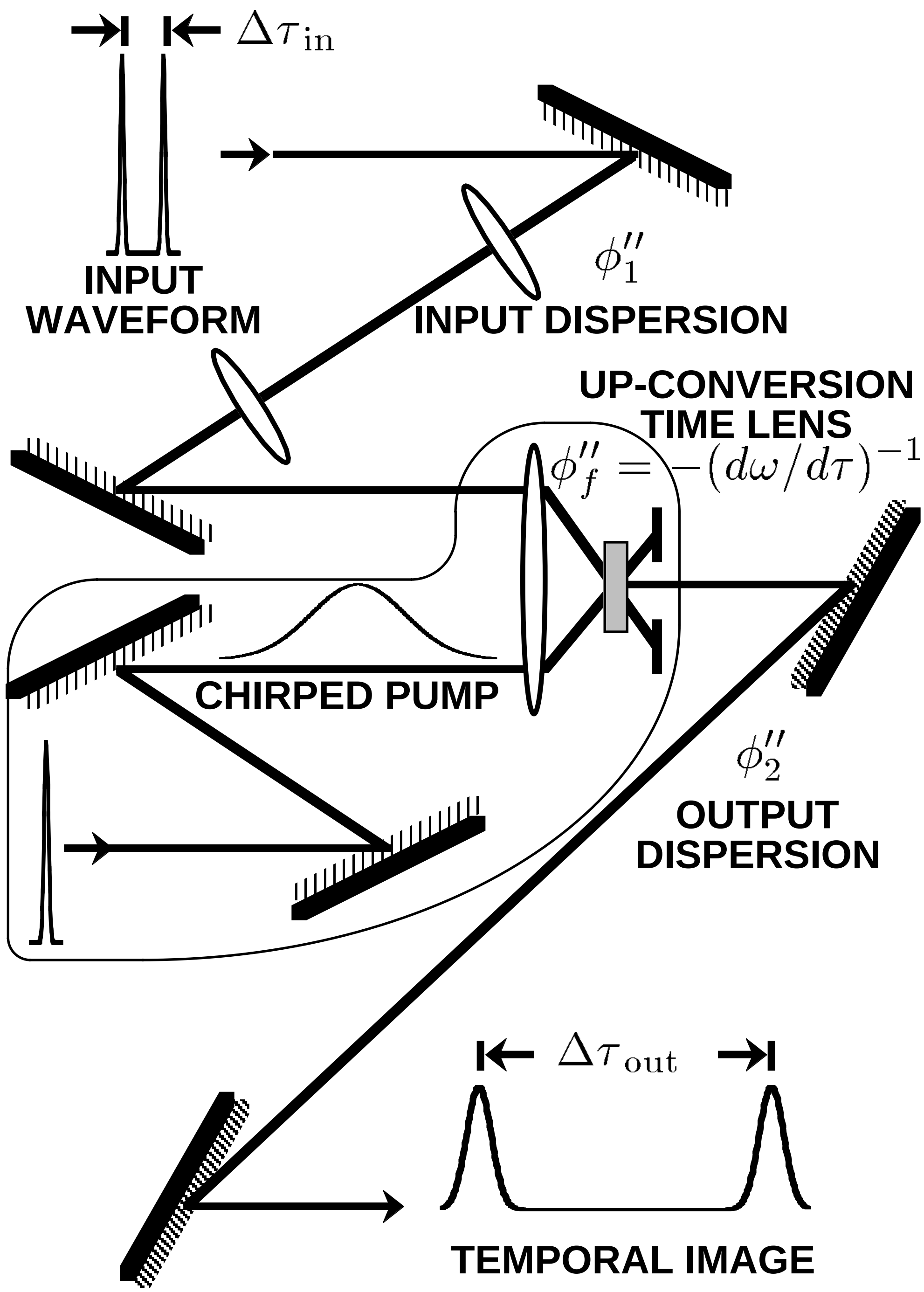
Figures

Fig. 1. An up-conversion temporal imaging system with positive magnification. In temporal imaging narrowband dispersion plays the role of paraxial diffraction and imparting a quadratic temporal phase (or linear frequency chirp) through sum-frequency generation acts as a time lens. The input and output GDD are opposite in sign, similar to "virtual" spatial imaging systems, but in this case they produce a real measurable image.

Fig. 2. A series of temporal images recorded at the output of the system with changing delay between the two input pulses, $\Delta\tau_{\text{in}}$, in Fig. 1. The input waveform is made up of two 87 fs pulses. Pulse #2 is delayed by an additional 667 fs with respect to pulse #1 between each measurement. A fit to the position of pulse #2 gives a magnification of $M = +103$ with an error of 73 fs rms referred to the input. The ringing after each pulse is due to the impulse response of the photodiode, **not** aberrations in the temporal imaging system.



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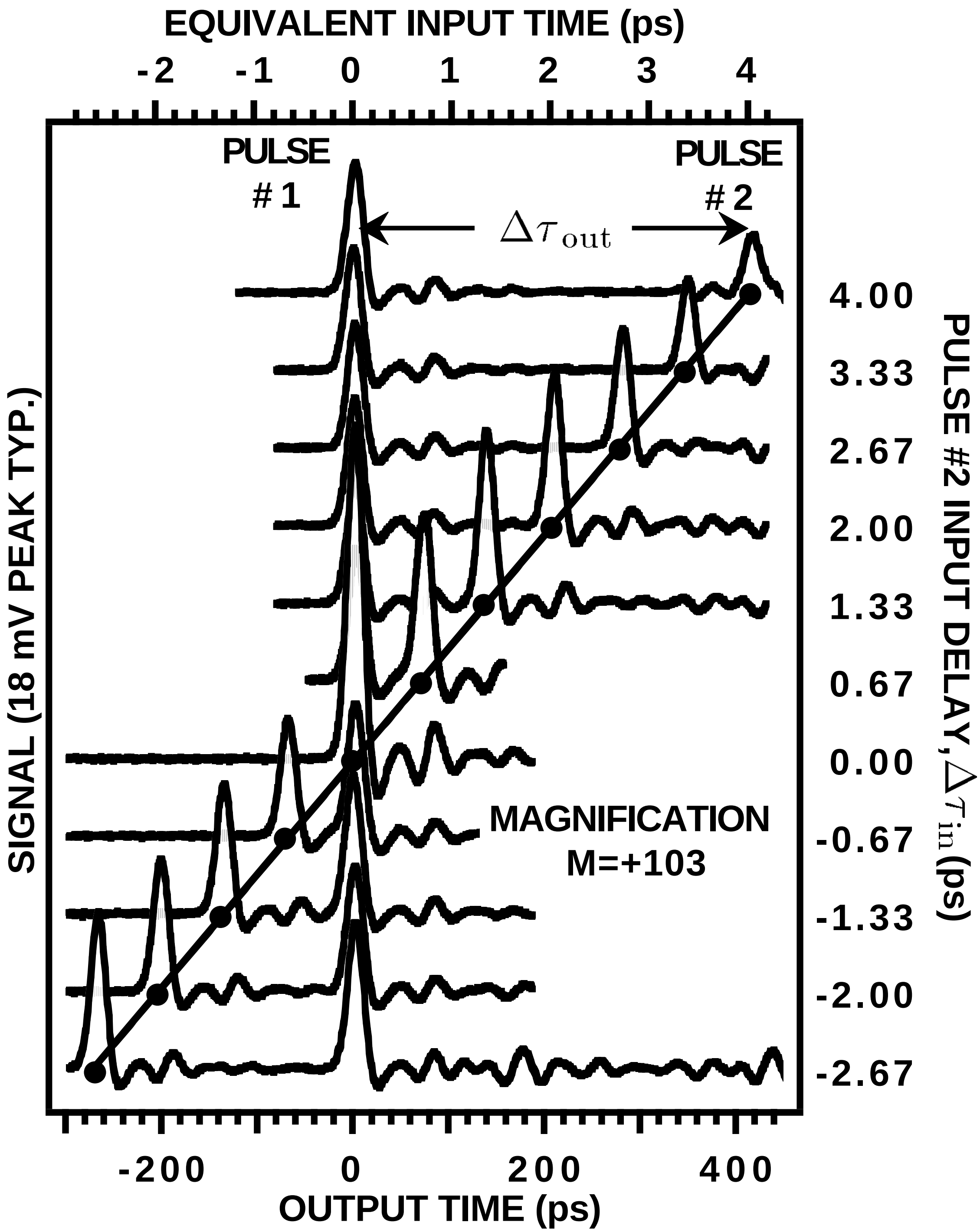

CLEO '99, Fig. 2 , C. V. Bennett and B. H. Kolner, "Temporal Imaging..."